AR-009-659

DSTO-TR-0320

The Weld Cracking Susceptibility of High Hardness Armour Steel

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Aeronautical and Maritime Research Laboratory

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ABSTRACT

The work detailed in this paper was performed to determine the likelihood of cracking during and after welding of 10 mm thick, high hardness, armour steel plate in conditions of high restraint. All welding was performed using the pulsed gas metal arc welding process in the flat position. High restraint conditions were tested using the Y-groove test.

Welds were performed with ferritic, austenitic and duplex austenitic /ferritic electrodes. Underbead cracking, a typical form of hydrogen induced cracking, was observed in the hardened region of the heat affected zone of ferritic welds where the heat input was 0.5 kJ/mm and the preheat was 75°C or less. No cracking was observed at this heat input when the preheat was raised to 150°C. When the heat input was raised to 1.2 kJ/mm, no cracking was observed, even when preheat was not used. Underbead cracking was not observed in either austenitic or duplex welds. However, the duplex welds were found to be susceptible to weld metal solidification cracking when the heat input used was low, 0.5 kJ/mm. These cracks did not occur when the heat input was raised to 1.2 kJ/mm.

RELEASE LIMITATION

Approved for public release

DEPARTMENT OF DEFENCE

DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

Published by

DSTO Aeronautical and Maritime Research Laboratory
PO Box 4331
Melbourne Victoria 3001

Telephone: (03) 9626 8111
Fax: (03) 9626 8999

AR No. 009-659
March 1996

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Executive Summary

High hardness armour steels, of the type used in the Australian Army's wheeled light armoured vehicle (LAV-25), are prone to weld cracking if inappropriate welding techniques are used in their fabrication and repair. Particular problems are hydrogen induced cold cracking in the hardened region of the weld heat affected zone and solidification cracking in the weld metal. Cracking is exacerbated if the plates to be welded are highly restrained, a condition typically encountered in LAV-25 repair situations.

Welding trials were performed on highly restrained plate sections used to simulate weld repair conditions. Available hydrogen was minimised by attention to thorough cleanliness and the use of the gas metal arc welding process to eliminate welding flux, a potential source of hydrogen pick-up.

This work has shown that high hardness armour steels, under conditions of high restraint, can be successfully welded using the pulsed gas metal arc welding process utilising ferritic, austenitic stainless steel and duplex austenitic/ferritic stainless steel electrodes. However, potential sources of hydrogen must be minimised and the levels of heat input and preheat must be kept within the closely controlled limits specified in this report, if cracking is to be avoided. The use of stainless steel electrodes are preferred due to the improved resistance to hydrogen induced cracking.

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Contents

1. Introduction

The need to minimise vehicle mass while achieving an adequate level of ballistic protection has led designers, in some instances, to the use of relatively thin, high hardenability steels for light armoured vehicle (LAV) hulls. The LAV-25 vehicle, currently in service with the Australian Army, is an example of such a design philosophy.

The majority of armour fabrication is performed by fusion welding. During this process the heat introduced into the plate during welding coupled with the high hardenability of the steel, can lead to the formation of high hardness regions within the weld heat affected zone (HAZ). The levels of hardness and residual stress in this region are dependent on the hardenability of the steel and the cooling rate of the plate after welding. The tendency for the HAZ to crack is related to a number of factors, including the hardness and microstructure of the steel, the level of tensile residual stress and the level of hydrogen which diffuses to this region during and after welding. Diffusible hydrogen, in the form of atomic hydrogen, is absorbed into the weld pool during welding. It can result from dissociation of moisture in the welding flux, where used, or from the surrounding atmosphere and from hydrocarbons, scale and rust on the test plates. As a consequence, careful selection of the appropriate welding process and consumables and detailed attention to clean housekeeping in the fabrication shop must be made to limit the amount of hydrogen present and to minimise the hardness and residual stress of this zone.

During welding, cracks may also develop in the weld metal in the hot and cold condition for a variety of reasons and close attention must be paid to choosing the appropriate consumables and weld parameters, if crack free welds are to be produced.

In addition, the heat of welding also produces a tempered or softened zone of parent metal beyond the hardened zone. To keep this softening effect to a minimum, the heat input of welding must also be kept within controlled limits.

To determine the susceptibility of high hardness armour steel to cracking during and after welding, especially under conditions of high restraint, a series of cracking tests were performed to determine the optimum welding conditions to produce crack free welds with a minimum of softening of the surrounding steel.

2. Experimental

The steel used in this work was 10 mm thick, Bisalloy 500 plate. The steel was supplied by Bisalloy Steels Pty Ltd., Unanderra, Australia. The chemical composition and typical mechanical properties of the steel, as stated in the manufacturers datasheets [1] are shown in Tables 1 and 2 respectively.

Table 1: Typical chemical composition of Bisalloy 500

Element	C	P	Mn	Si	S	Ni	Cr	Mo	Al	Ti	B
Wt %	0.32	0.025	0.7	0.3	0.008	0.35	1.20	0.25	0.07	0.03	0.002

Table 2: Typical mechanical properties of Bisalloy 500

0.2 % Proof Strength	1580 MPa
Ultimate Tensile Strength	1640 MPa
% Elongation (50 mm G.L).	10 %
Charpy V-notch (Longitudinal)	31 J
Hardness	477 - 534 HB $_{3000/10}$

Bisalloy 500 was chosen because it complies with the hardness requirement of 477 - 534 HB (509 - 568 HV) of Mil-A-46100D(MR) high hardness armour steel [2] and is manufactured in Australia. While no specific chemical composition is required for a steel to comply with this military specification, certain mechanical and ballistic requirements must be met.

The weldments were produced by the gas metal arc welding process, using a pulsed arc (GMAW-P). The absence of flux and the use of a shielding gas make this process a very low hydrogen process, and with the use of a pulsed arc, relatively low heat input welds can be produced. Pulsing of the current facilitates a spray mode of metal transfer at lower power levels than required in conventional GMAW. Spray transfer is desirable because it produces a stable, spatter free arc. Spray transfer in conventional GMAW is generally restricted to the flat or horizontal positions due to the need for continuous operation at relatively high currents. However, with GMAW-P the lower overall current levels used enable it to be utilised in all positions, a potential advantage in repair weld situations.[3].

Preliminary tests were performed using the controlled thermal severity (CTS), rigid restraint and Y-groove tests [4]. The Y-groove test proved to be the most sensitive to weld cracking and the specimen was relatively simple to fabricate. It was consequently chosen as the weld cracking test to be used in this work. This test is also appropriate because it simulates the highly restrained, groove welds likely to be encountered in a large number of armour repair situations. The Y-groove specimen is shown in Figure 1

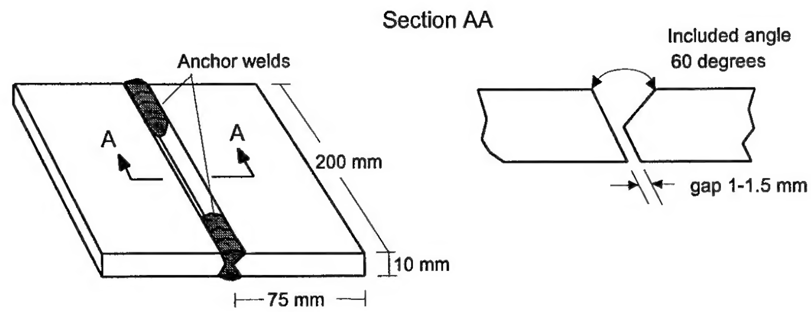


Figure 1: *Y-Groove specimen with detail of groove profile*

All the welds produced in this work were of the stringer bead type using direct current electrode positive and were performed in the flat position. A backhand technique, with a drag angle of 15 degrees was used. The nozzle to work gap was maintained at approximately 12 mm.

Test welds were made with three types of electrode: a ferritic steel, an austenitic stainless steel and a duplex austenitic/ferritic stainless steel. Welding was carried out using a Welding Industries of Australia (WIA)- CDT 240, GMAW-P welding machine. The electrodes were all selected to give undermatching strength of the fusion zone to the parent metal. This is advantageous in reducing the likelihood of weld cracking by reducing the level of weld restraint. The shielding gases were recommended by WIA for use with these electrodes. The electrodes and shielding gases used are as follows:

1. *CIGWELD Autocraft S6,* - complying with American Welding Society (AWS) A5.18-79, ER70-S6. This is a ferritic steel and is recommended by General Motors of Canada, Diesel Division for the production and repair of the LAV-25 vehicle, high hardness steel armour. [5] This electrode was also recommended by Bisalloy Steels for welding Bisalloy 500 steel [1]. The electrode diameter was 0.9 mm and the shielding gas was CIGWELD Argoshield 51 (75% Ar, 25% CO_2) at a flow rate of 13 litres/min.
2. *Bohler 310* - complying with AWS A5.9 ER310. This is a fully austenitic stainless steel. The electrode diameter was 0.9 mm and the shielding gas was CIGWELD Argoshield 60 (98.5% Ar, 1.5% O_2) at a flow rate of 13 litres/min.
3. *Avesta P7,* - complying with AWS A5.9 ER312. This is a duplex austenitic/ferritic stainless steel. The electrode diameter was 0.9 mm and the shielding gas was CIGWELD Argoshield 61 (65% Ar, 30% He and 5% CO_2) at a flow rate of 13 litres/min.

Stainless steel electrodes were tested because it is reported [6] that weldments produced with these consumables are less prone to hydrogen induced cracking in the hardened HAZ. This cracking resistance is attributed to the greater solubility of hydrogen in austenite than in either martensite or ferrite, and the low diffusivity of hydrogen in austenite.

The tests conducted used a range of preheat and heat input to determine the effect that these parameters have on the crack susceptibility of this material. The preheat was applied using electric resistance heated ceramic pads mounted on the underside of the plate to be welded. The temperature on the top side of the plate was monitored with a digital thermometer utilizing a thermocouple contact probe. Welding was performed when the temperature of the plate, within 50 mm of the weld preparation, had uniformly reached the desired preheat temperature. The heat input is calculated as follows:

$$\text{Heat input (HI)} = V * I / t$$

Where V = Arc voltage (RMS value for A.C.)
I = Welding current in amperes (RMS value for A.C.)
t = Travel speed in mm/s

HI is expressed as kJ/mm

All tests specimens were clamped rigidly to a 25 mm thick steel backing plate to prevent distortion during welding and to maintain a condition of high restraint. After welding, the assembly was left for 3 days to allow time for cracks to develop. The specimens were then sectioned transversely, midway along the weld and the sections ground and polished and examined for cracks using a metallurgical microscope.

A hardness traverse was then performed on selected sections to determine the effect of the various welding conditions on plate hardness. The hardness traverse for all specimens was located 2 mm below the plate surface to eliminate the effects of partial surface decarburisation. The hardness impressions were spaced at 1 mm intervals. The hardness traverse location is shown in Figure 2

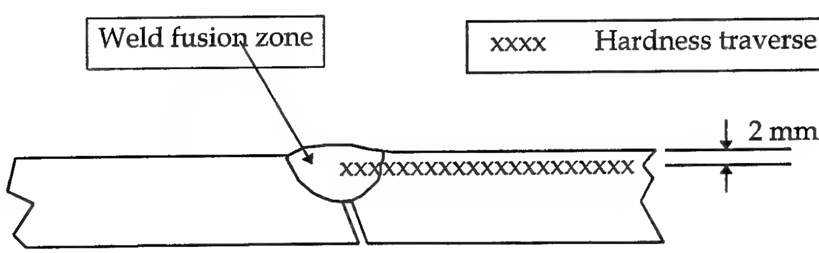


Figure 2: Location of hardness traverse on weldment section

3. Results

Welding of Bisalloy 500 produces three distinct zones at and adjacent to the weld. See Figure 3. The zones are:

1. Fusion zone (FZ)
2. Rehardened, heat affected zone (RH-HAZ) where partial or total re-austenitisation occurs during welding followed by quenching by the surrounding plate after welding.
3. Tempered, heat affected zone (T-HAZ) where the temperature of welding is not sufficiently high to produce re-austenitisation, but where a tempering of the surrounding parent metal occurs.

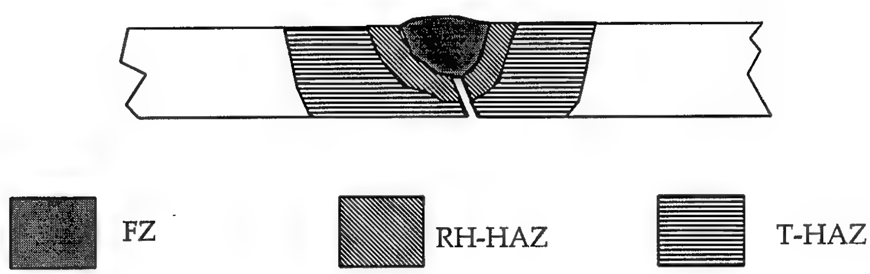


Figure 3: *Schematic diagram of section from Y-groove weldment showing the three zones*

3.1 Cracking

Details of the parameters used in the welding trials and the results of the cracking tests are shown in Table 3.

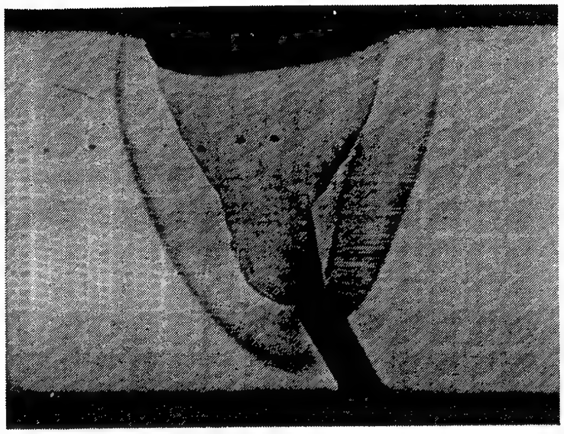
Table 3: Welding parameters used in Y-groove testing program

Weldment	Electrode	Preheat (°C)	Voltage (V)	Current (A)	Travel Speed (mm/s)	Heat Input (kJ/mm)	Cracked weldment
F1	Ferritic	19	28	186	9.5	0.5	Yes*
F2	Ferritic	14	29	180	9.5	0.5	Yes*
F3	Ferritic	18	28	186	4.3	1.2	No
F4	Ferritic	75	29	180	9.5	0.5	Yes*
F5	Ferritic	75	28	192	4.3	1.3	No
F6	Ferritic	150	27	195	9.5	0.5	No
F7	Ferritic	150	27	198	4.3	1.2	No
A1	Austenitic (310)	17	28	186	9.5	0.7	No
A2	Austenitic (310)	18	27	189	3.7	0.9	No
FA1	Ferritic-Austenitic (312)	16	28	186	9.5	0.5	Yes #
FA2	Ferritic-Austenitic (312)	18	27	189	3.7	1.4	No
FA3	Ferritic-Austenitic (312)	75	27	189	9.5	0.5	Yes #
FA4	Ferritic-Austenitic (312)	150	29	177	4.3	1.2	No

* - crack initiated at weld root in HAZ adjacent to fusion boundary and propagated towards weld toe.
# - crack located at centre line of fusion zone

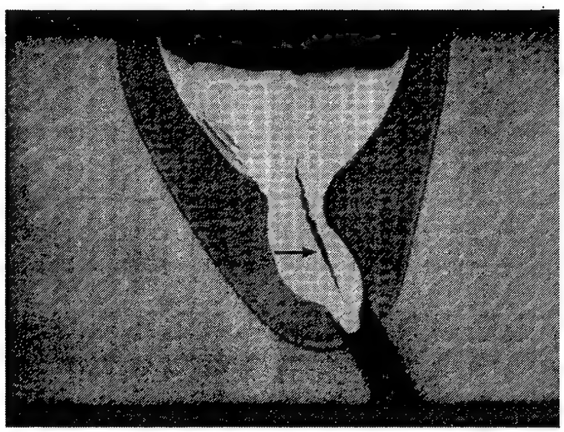
Two types of cracks were observed in the sections examined: Firstly, under bead cracks, which initiated at the weld root and travelled through the rehardened heat affected zone towards the weld toe. This crack type is typical of hydrogen induced cracking and was only observed in the ferritic welds fabricated using 0.5 kJ/mm heat input and preheat at or below 75°C. A typical example of this type of crack is shown in Figure 3. This crack type did not occur when a heat input of 1.2 kJ/mm was used, regardless of preheat, or when a preheat of 150°C was used in conjunction with the lower heat input level. Secondly, a weld centreline, solidification crack occurred in the 312 stainless steel weld metal when a heat input of 0.5 kJ/mm was used in conjunction with a preheat of 75°C or less. A typical crack of this type is shown in Figure4. This form of cracking did not occur when the heat input was raised to 1.4 kJ/mm with no preheat or 1.2 kJ/mm at a preheat of 150°C. The larger heat input produced a weld having a lower depth to width ratio.

No cracks were observed in any of the welds produced using the 310 stainless steel electrode, regardless of the preheat and heat input used.



Mag. 6X approx.

Figure 4: Typical example of an underbead crack (arrowed) with its origin at the weld root. These cracks were located entirely within the rehardened region of the weld heat affected zone.



Mag. 6X approx.

Figure 5: Weld centreline solidification crack (arrowed) in 312 stainless steel weld metal resulting from the large depth to width ratio of fusion zone welded with low heat input

3.2 Hardness

Hardness traverses, using a Vickers hardness machine, were conducted on sections from selected weldments as discussed in the Experimental section of this report. A typical hardness profile is shown in Figure 6. The effective HAZ comprises the RH-HAZ and T-HAZ and is included as an expression of the degree of plate softening resulting from welding. It is based on clause 5.1.3 in MIL- STAN-1185 (AT) [7] which

states that on any ballistic surfaces 5/8 inch (15.9 mm) from toe of the weld, at any location of weldment, the Brinell hardness shall not be lower than that permitted by MIL-A-46100 [2]. This limit of hardness is 477 HB (equivalent to 509 HV). Detailed results of the hardness measurements and the size of the zones are shown in Table 4.

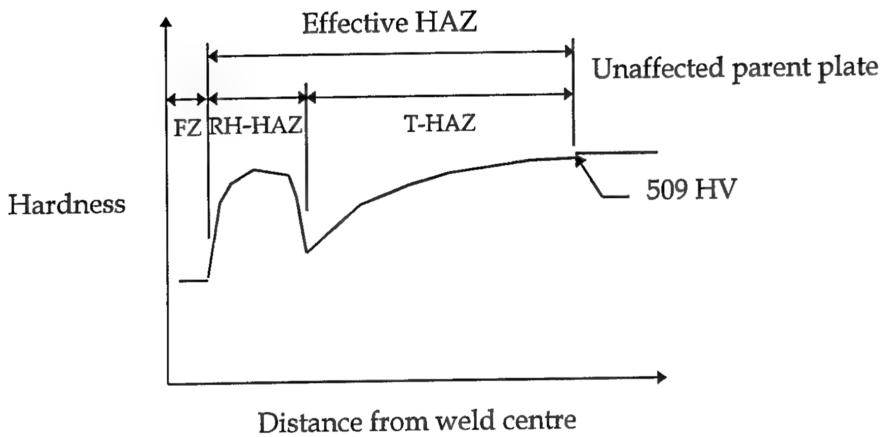


Figure 6: *Schematic diagram of typical weldment hardness profile*

Table 4: *Weldment hardness*

Weldment (Details Table 3)	Preheat (°C)	Heat Input (kJ/mm)	FZ Hardness (Min/Max) (HV 10)	FZ Zone Size * (mm)	RH-HAZ Hardness (Min/Max). (HV 10)	RH-HAZ Zone Size * (mm)	Effective HAZ Hardness (Min.) (HV 10)	Effective HAZ Zone Size * (mm)
Ferritic								
F1	-	0.5	254/268	2.5	498/540	1.5	342/542	7.5
F3	-	1.2	232/235	3.3	415/478	4.5	320/539	17.5
F6	150	0.5	266/272	2.5	401/508	2.0	351/525	13.5
F7	150	1.2	228/234	3.3	397/457	4.0	319/500	24.5
Austenitic								
A1	-	0.7	168/197	1.5	473/514	2.8	336/545	8.5
A2	-	0.9	180/233	1.7	519/536	3.8	351/554	13.0
Ferritic / Austenitic								
FA1	-	0.5	233/241	2.0	495/515	1.3	376/536	7.0
FA2	-	1.4	224/228	2.3	366/508	5.0	327/554	15.5
FA4	150	1.2	225/230	2.0	380/421	5.0	326/515	22

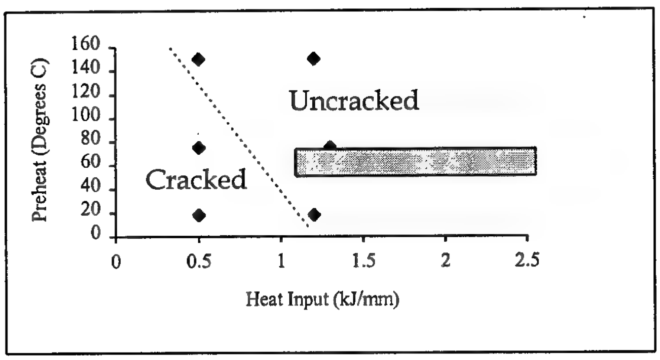
* The zone sizes were estimated, in accordance with Figure 6., from the hardness traverse performed on a section from each weldment

4. Discussion

4.1 Ferritic Weld Metal

Both Bisalloy Steels Pty. Ltd. and General Motors of Canada specify that American Welding Society electrode AWS ER70-S6 and the GMAW process are suitable for weld fabrication of their high hardness steels. However, the preheat and heat input specifications vary greatly. In the former case, a preheat of 50 - 75°C and a heat input of 1.0 - 2.5 kJ/mm is specified for plate of thickness of 6 - 13 mm. In the latter case, a preheat of 75°C is specified if the ambient temperature is less than 10°C. If the ambient temperature is 10°C or greater, no preheat is required. In this specification no limits of heat input were stated.

In this work it was found that under the high restraint conditions of the Y-groove test, cracking did occur at very low heat inputs, 0.5 kJ/mm, when the preheat was at or below 75°C. No cracks were observed when a preheat of 150°C was used. When the heat input was increased to 1.2 kJ/mm no cracking occurred, regardless of the preheat temperature. The incidence of cracking is summarised in Figure 7.



Heat input and preheat limits recommended by Bisalloy Steels Pty. Ltd.

Figure 7: Relationship between preheat, heat input and HAZ cracking of ferritic welds. The dotted line represents the approximate demarcation between cracking and non cracking conditions. The weld parameters trialed are shown by ◆

The tendency for HAZ cracking has been studied widely [8-12] and is generally attributed to the occurrence of three simultaneous factors:

1. ***A high level of diffusible hydrogen*** - this may be limited by restricting potential hydrogen sources, as discussed earlier.
2. ***A high level of tensile stress*** - this stress is dependent on the level of weld restraint which is a factor of plate thickness and joint design. While the steel armour used on high hardness LAV's may be considered to be relatively thin, the

geometries of some weldments, especially in repair situations, can produce high levels of restraint. Thermal stress relief treatments are often used to reduce prevailing residual stresses. However, the temperature used in such treatments should not exceed the tempering temperature of the steel to be welded. Due to the low tempering temperature of Bisalloy 500 (175°C) a stress relief heat treatment was not used in this work.

3. ***A susceptible microstructure*** - for example, high hardness martensite. The hardness of the martensite can be reduced by using higher levels of preheat and heat input to reduce the cooling rate in the HAZ.

In this work considerable care was taken to limit available sources of hydrogen by using the GMAW process which negated the need for the use of flux, using appropriate shielding gas at optimum gas flow rates, ensuring that scale, rust and hydrocarbons were removed from the weldment, and ensuring that the electrode was clean.

The hardness and size of the three weld zones are detailed in Table 4. It can be seen that these parameters are also affected by the levels of heat input and preheat used during welding, and in the case of the fusion zone, the type of electrode used. The hardness ranges for each of the zones are summarised graphically in Fig 8.

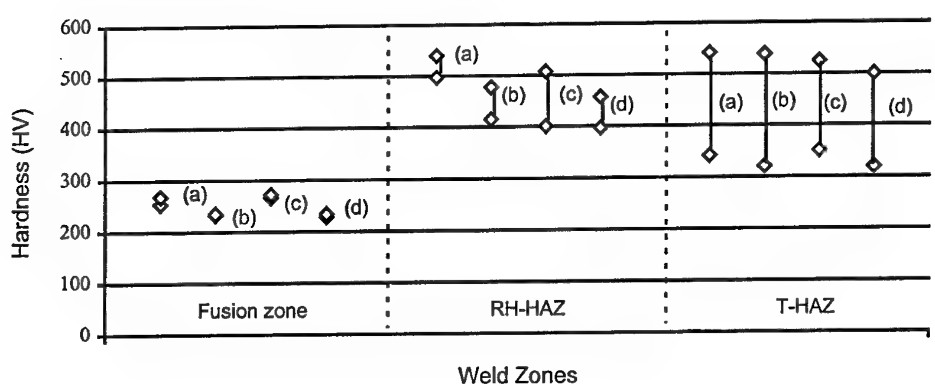


Figure 8: Hardness of weld zones for various combinations of heat input and preheat with the ferritic electrode

a. Heat input 0.5 kJ/mm, no preheat
b. Heat input 1.2 kJ/mm, no preheat
c. Heat input 0.5 kJ/mm, 150 °C preheat
d. Heat input 1.2 kJ/mm, 150 °C preheat

The hardness of the fusion zone ranged from 228 HV_{10} to 272 HV_{10}, depending on the levels of heat input and preheat used. This represents a hardness of the order of 50% of that of the original plate (540 HV_{10}). The size of this zone increased by about 30% when the heat input was raised from 0.5 kJ/mm to 1.2 kJ/mm and the preheat was raised from room temperature to 150°C.

In the RH-HAZ the maximum hardness measured for any weld produced was 540 HV_{10} (Heat input 0.5 kJ/mm and no preheat) which is equivalent to the original hardness of the plate. The use of the higher heat input (1.2 kJ/mm) or the lower heat input (0.5 kJ/mm) combined with a preheat of 150°C, reduced the maximum measured hardness in this region to approximately 90% and 95% of that of the original plate, respectively. The combined effect of raising the heat input from 0.5 to 1.2 kJ/mm and using a preheat of 150°C reduced the maximum hardness to 457 HV_{10} (85% of the original plate hardness). The size of this zone was found to be greatly affected by the amount of heat input used with the 1.2 kJ/mm level producing a zone size 200% greater than the 0.5 kJ/mm level. The level of preheat also increased the zone size, but to a much smaller extent than the heat input.

The hardness reductions in the RH-HAZ, brought about by increasing the levels of heat input and preheat are relatively modest and may not fully account for the elimination of cracking in these zones. A concomitant reduction in residual stress may also help to eliminate the conditions necessary to cause cracking.

Softening in the T-HAZ was also found to be significant, although the minimum hardness measured in this zone was greater than in the fusion zone. The minimum hardness in the T-HAZ (heat input 0.5 kJ/mm and no preheat) was approximately 60% of that of the original plate. When the heat input level was increased to 1.2 kJ/mm and a preheat of 150°C was used, the minimum T-HAZ hardness also decreased to approximately 60% of that of the original plate. The zone size was also significantly affected by the level of heat input and preheat used. The zone size increased from 9 to 23 mm (156%) when the heat input and preheat were raised from 0.5 kJ/mm heat input, room temperature preheat to 1.2 kJ/mm heat input, 150°C preheat.

It should be noted that the effective HAZ size requirement of Mil-Stan-1185 [7] of 15.9 mm was exceeded when a preheat of 150 °C and a heat input of 1.2 kJ/mm was used.

Softening of armour plate during welding can be expected to reduce both the structural strength and ballistic penetration resistance of armour steel. This is most important in vehicles such as the LAV-25 where the armour plate is an important structural member. The degree of softening must be limited as much as possible consistent with the production of crack free welds.

4.2 Austenitic Stainless Steel Weld Metal

The austenitic electrode used complies with AWS A5.9 ER310. Due to its high alloy content it can tolerate up to 67% dilution by the parent metal without the formation of weld metal martensite.[6]. In this work the level of dilution ranged from 25 to 30 % and a fully austenitic fusion zone was produced. Due to the low diffusivity of hydrogen in austenite, a fully austenitic weld metal will limit the amount of hydrogen diffusing to the HAZ and consequently, reduce the likelihood of hydrogen induced cracking in this region. This resistance to HAZ cracking is reflected in this work by the fact that no cracking was observed in these welds even with no preheat and low heat input levels (0.7 and 0.9 kJ/mm). The hardness of the fusion zone is

relatively low (168 - 233 HV_{10}) when compared with those produced with the other electrodes and poorer structural strength would be expected. The hardness profiles and zone sizes of the RH-HAZ and T-HAZ were similar to those produced using the ferritic electrode when similar heat input and preheat were used. The hardness ranges for each weld zone are summarised in Figure 9.

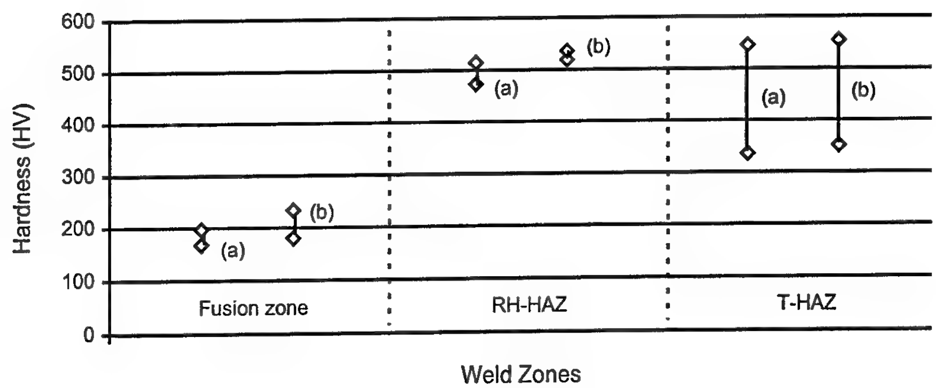


Figure 9: Hardness of weld zones produced with the austenitic electrode

a. Heat input 0.7 kJ/mm, no preheat
b. Heat input 0.9 kJ/mm, no preheat

4.3 Duplex Stainless Steel Weld Metal

The duplex stainless steel electrode used complies with AWS A5.9 ER312. Centre-line cracks were observed in the fusion zone of these welds when the heat input was low (0.5 kJ/mm). These weld metal cracks can occur for a number of reasons, including too high a weld depth to width ratio or too small a bead size coupled with high restraint conditions. In this work it was found that increasing the heat input to 1.2 kJ/mm reduced the depth to width ratio of the fusion zone and eliminated the centreline cracking problem. No other cracks were observed in these weldments at any of the levels of heat input and preheat used. The fusion zone hardness did not vary greatly with the heat input and preheat used, and was marginally below the hardness of the ferritic electrode fusion zones. The hardness profiles and zone sizes of the RH-HAZ and T-HAZ were similar to those produced using the two other electrode types when similar heat input and preheat were used. The hardness ranges at various heat input and preheat levels are summarised in Figure 10.

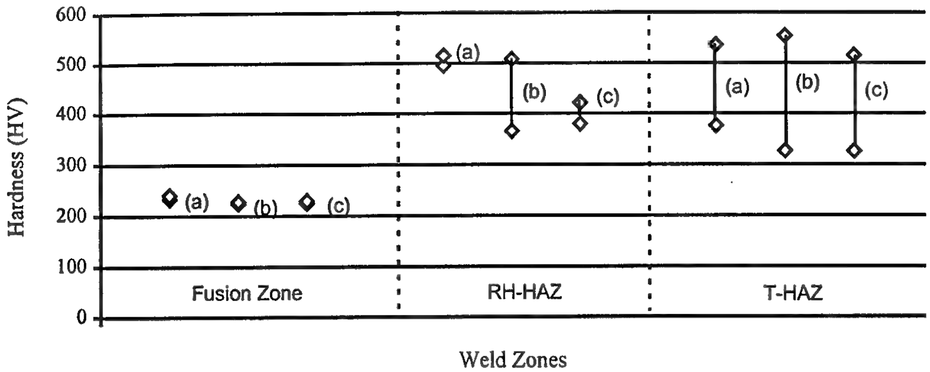


Figure 10: Hardness of weld zones produced with the duplex stainless steel electrode

- *a.* *Heat input 0.5 kJ/mm, no preheat*
- *b.* *Heat input 1.4 kJ/mm, no preheat*
- *c.* *Heat input 1.2 kJ/mm, 150 °C preheat*

4.4 General Comments

It should be noted that where the welding quality must comply with MIL-STD-1185(AT) [7] then the level of preheat and heat input must be limited. In this work, welds produced using a preheat of 150 °C and a heat input of 1.2 kJ/mm, exceeded the softening zone limits set down by at least 38 %. All of the other welds produced complied with this limit.

Many factors combine to cause weld cracking of high hardenability armour steels, especially in production and repair welding where conditions such as degree of restraint, levels of preheat and heat input, thermodynamics in the plate, welding position and sequence may all be quite variable. It is therefore extremely difficult to quantify the conditions necessary to prevent cracking in all situations. The best form of weldability test is the full scale trial weld which involves all of the factors which will cause cracking. However, this can be an expensive method to test the suitability of consumables and welding parameters. Small scale tests like those utilising the y-groove specimen are useful in giving an indication of procedures likely to produce crack free welds, but some weld trialing using situations more closely related to real vehicle welding will be necessary in order to optimise conditions for production or repair welding.

5. Conclusions

The 10 mm thick, Bisalloy 500 steel plate can be readily welded by the pulsed-GMAW process using the three electrodes trialed in this work, if precautions are taken to limit potential hydrogen sources and appropriate levels of heat input and preheat are used. However, it is recommended that either of the austenitic consumables examined in this work should be used in preference to the ferritic consumable due to their greater resistance to hydrogen induced cracking.

Based on this work and the Bisalloy Steels handbook it is recommended that heat input levels should be 1.0 - 2.5 kJ/mm and the preheat should be 50 - 75°C. These limits are considered to be reasonably conservative and should allow for welding in workshop conditions.

Significant softening is caused by welding these steels, especially in the fusion zones when using undermatched electrodes such as those utilised in this work. The greatest hardness reduction was measured in the austenitic stainless steel fusion zone where the hardness measured was as low as 31% of that of the original plate. With the other electrodes used, the reduction in hardness was less severe. The minimum hardness of the ferritic fusion zones ranged from 42% to 49% of the original plate hardness, depending on the level of heat input and preheat used. The hardness of the duplex stainless steel fusion zone approached the lower hardness level of the ferritic fusion zones.

6. Acknowledgements

The author wishes to thank Dr R. Phillips for advice given during the course of this work, and Alban Cole and Paul Calleja for technical assistance.

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DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION DOCUMENT CONTROL DATA					1. PRIVACY MARKING/CAVEAT (OF DOCUMENT)
2. TITLE The Weld Cracking Susceptibility of High Hardness Armour Steel			3. SECURITY CLASSIFICATION (FOR UNCLASSIFIED REPORTS THAT ARE LIMITED RELEASE USE (L) NEXT TO DOCUMENT CLASSIFICATION) Document (U) Title (U) Abstract (U)		
4. AUTHOR(S) S.J. Alkemade			5. CORPORATE AUTHOR Aeronautical and Maritime Research Laboratory PO Box 4331 Melbourne Vic 3001		
6a. DSTO NUMBER DSTO-TR-0320	6b. AR NUMBER AR-009-659		6c. TYPE OF REPORT Technical Report	7. DOCUMENT DATE March 1996	
8. FILE NUMBER 510/207/0388	9. TASK NUMBER ARM 94/133	10. TASK SPONSOR ARMY	11. NO. OF PAGES 17	12. NO. OF REFERENCES 12	
13. DOWNGRADING/DELIMITING INSTRUCTIONS			14. RELEASE AUTHORITY Chief, Ship Structures and Materials Division		

15. SECONDARY RELEASE STATEMENT OF THIS DOCUMENT

Approved for public release

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16. DELIBERATE ANNOUNCEMENT

No limitations

17. CASUAL ANNOUNCEMENT Yes

18. DEFTEST DESCRIPTORS

High Hardness Armour Steel; Welding; Solidification Cracking; Hydrogen Induced Cracking

19. ABSTRACT
The work detailed in this paper was performed to determine the likelihood of cracking during and after welding of 10 mm thick, high hardness, armour steel plate in conditions of high restraint. All welding was performed using the pulsed gas metal arc welding process in the flat position. High restraint conditions were tested using the Y-groove test. Welds were performed with ferritic, austenitic and duplex austenitic /ferritic electrodes. Underbead cracking, a typical form of hydrogen induced cracking, was observed in the hardened region of the heat affected zone of ferritic welds where the heat input was 0.5 kJ/mm and the preheat was 75°C or less. No cracking was observed at this heat input when the preheat was raised to 150°C. When the heat input was raised to 1.2 kJ/mm, no cracking was observed, even when preheat was not used. Underbead cracking was not observed in either austenitic or duplex welds. However, the duplex welds were found to be susceptible to weld metal solidification cracking when the heat input used was low (0.5 kJ/mm). These cracks did not occur when the heat input was raised to 1.2 kJ/mm.